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SPATIOTEMPORAL DISTRIBUTION CHARACTERISTICS AND VARIATION TRENDS OF HIERARCHICAL PRECIPITATION IN GUANGDONG PROVINCE OVER THE PAST 50 YEARS

LIU Xian-tong (刘显通)[1], ZHENG Teng-fei (郑腾飞)[1, 2], WAN Qi-lin (万齐林)[1], YU Xin (于 鑫)[3]
(1. Guangzhou Institute of Tropical and Marine Meteorology, CMA, Guangzhou 510640 China; 2. State Key Laboratory of Severe Weather, Chinese Academy of Meteorological Sciences, Beijing 100081 China; 3. Guangdong Provincial Meteorological Observatory, Guangzhou 510640 China)

Abstract: The climatic characteristics of the precipitation in Guangdong province over the past 50 years were analyzed based on the daily rainfall datasets of 86 stations from 1961 to 2010. The rainfall was divided into five categories according to its intensity, and their spatiotemporal characteristics and variation trends were investigated. The annual rainfall amount was within 1,500 to 2,000 mm over most parts of Guangdong, but substantial differences of rainfall amount and rainy days were found among different parts of the province. There were many rainy days in the dry seasons (October to March), but the daily rainfall amounts are small. The rainy seasons (April to September) have not only many rainy days but also heavy daily rainfall amounts. The spatial distributions of light rainy days (1 mm<P< 10 mm) and moderate rainy days (10 mm<P< 25 mm) resemble each other. The heavy rainy days (25 mm<P< 50 mm), rainstorm days (50 mm<P< 100 mm) and downpour days (P> 100 mm) are generally concentrated in three regions, Qingyuan, Yangjiang, and Haifeng/Lufeng. The average rainfall amount for rainy days increases form the north to the south of Guangdong, while decreasing as the rainfall intensity increases. The contributions from light, moderate and heavy rain to the total rainfall decreases form the north to the south. The annual rainy days show a decreasing trend in the past 50 years. The light rainy days decreased significantly while the heavy, rainstorm and downpour rainy days increased slightly. The annual total rainfall amount increased over the past 50 years, which was contributed by heavy, rainstorm and downpour rains, while the contribution from light and moderate rains decreased.

Key words: spatiotemporal distribution; rainfall amount; rainy days; rainfall contribution rate
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1 INTRODUCTION

In the context of global climate changing, precipitation is one of the most apparent response factors and a key direction in meteorological research. According to the 4th assessment report of the IPCC, heavy precipitation events happened on an increasing frequency throughout the world and showed a trend of further development in the last few decades [1]. Researchers have conducted studies on the relationship of droughts and floods with precipitation [2-5], and even on the change characteristics of the number of days of different levels of precipitation [6-12]. However disasters, such as droughts and floods, are not only related to precipitation, but also greatly related to the number of precipitation days and the precipitation contribution rate. The changes of precipitation day and precipitation contribution rate at different levels may directly or indirectly reflect the precipitation climate characteristics of the regions under study. In particular, short-term, heavy precipitation events may reflect local flood disasters, which are of great guiding significance for the study of droughts and floods[13, 14].

Situated in South China, Guangdong is close to the northwest Pacific Ocean and the South China Sea[15]; the climate of Guangdong is a South Asian Subtropical Climate. Guangdong is one of the provinces with the highest precipitation in China, and the annual mean precipitation is 1,780mm [16, 17]. The heavy precipitation regions of Guangdong are mainly distributed in three downpour centers, i.e. the Beijiang River valley, eastern Guangdong and windward slopes in western Guangdong. The rainy season of Guangdong lasts from April to September every year. The precipitations in the annually first rainy season (April–June) are the frontal

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Biography: LIU Xian-tong, Ph.D., Research Assistant, primarily undertaking research on cloud precipitation physics and numerical forecast of severe weather.
Corresponding author: WAN Qi-lin, e-mail: qlwan@grmc.gov.cn

precipitation and the tropical monsoon precipitation. During the annually second rainy season (July – September), the precipitations are mainly caused by tropical cyclones[18, 19].

Due to the distance from the south to the north, the different regions of Guangdong are differently affected by weather systems, which results in the uneven spatiotemporal distribution of precipitation and the huge difference in annual precipitation level in the geography. Such a difference results in the central heavy precipitation regions suffering from rainstorm disasters, and the following floods, debris flows, landslides and other disasters cause severe damage to the local economy, production and property safety[20]. Therefore, it is very important to study the precipitation climate characteristics and the rainfall level of Guangdong province. In the past, researchers have studied [24-28] the formation, tendency, cycles [21-23] and spatiotemporal distribution of precipitation; however these studies were not perfect [29]. In this study, the climatic characteristics of the precipitation in Guangdong and the characteristics of the precipitation in the three rainstorm centers of Guangdong from 1961 to 2010 were analyzed, and certain quantitative studies were made on the hierarchical precipitation of Guangdong.

2 DATA AND METHODS

2.1 *Data set and research methods*

The daily precipitation data of 86 meteorological observation stations provided by the Guangdong Meteorological Service Climate Center were analyzed in this study, and the locations of the meteorological stations are shown in Fig.1. Most of the regular meteorological stations of Guangdong province started their records in the 1950s, and complete observation data has been obtained since then. In order to ensure the comparability of the observation data between meteorological stations, the observed daily precipitation data for the 50 years from 1961 to 2010 were used to perform statistical analysis.

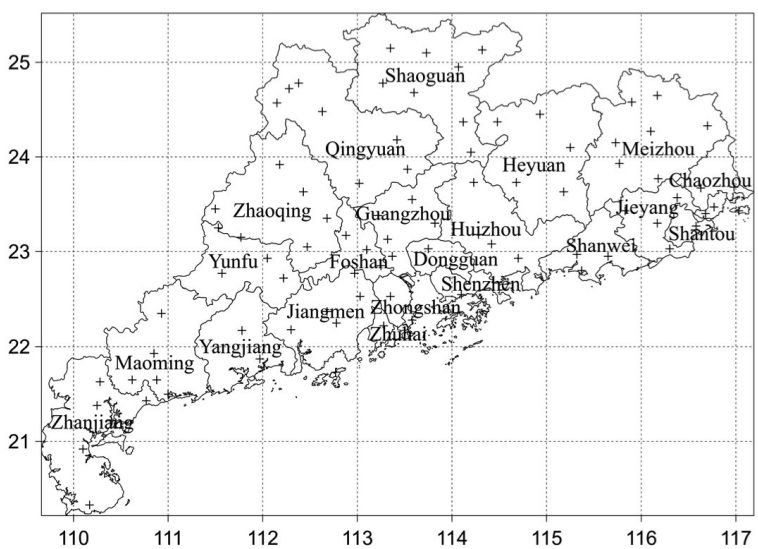

Figure 1. Distribution of the meteorological observation stations of Guangdong province (represented by "+").

The following analysis methods were used in the study: linear trend, moving average, correlation coefficient and composite analysis. Among these, the linear trend can help obtain the trend of hierarchical precipitation by establishing a simple linear regression equation [30, 31] and using the least square method where the computational formula is $x=b+at$. These statistical methods were tested by using the following methods: the regression coefficient of the linear trend was tested by using the F distribution function; the correlation coefficient was tested by using the t distribution density function; the composite analysis was verified by using the difference in the average value of two groups of samples; where the significance level was α=0.05[32].

2.2 *Rainfall classification method*

In order to study the contribution and influence of different hierarchical precipitation on the climate change of precipitation in Guangdong, the daily precipitation was classified following the method as shown in Table 1. It is based on the research results of Chen et al.[30] and the local characteristics of precipitation and climate, which is different from the daily meteorological operation standard method.

Table 1. Classification method of daily precipitation.

Precipitation grade	Precipitation/(mm/d)
Light rain	0.1–9.9
Moderate rain	10.0–24.9
Heavy rain	25.0–49.9
Rainstorm	50.0–99.9
Downpour	⩾100.0

3 RESULTS AND ANALYSIS

3.1 *Spatial distribution characteristics of precipitation*

The spatial distributions of the annual average precipitation (a) and the precipitation days (b) in Guangdong from 1961 to 2010 are shown in Fig.2. According to the statistical results, the annual average precipitation in Guangdong were usually between 1,500 and 2,000 mm, so there were abundant precipitation. The annual average precipitation was above 1,800 mm from central Guangdong to the coastal areas, the maximum value center of annual average precipitation appeared in the region of Yangjiang-Enping-Shangchuandao in the southwest coastal area. The highest value appeared at Enping station, with annual precipitation up to 2,531 mm. The spatial distribution of annual precipitation in Guangdong is very uneven, and there are three rainstorm centers with annual precipitation higher than 2,000 mm, namely the Enping-Yangchun-Yangjiang center at the southern foot of Yunwu Mountain, the Haifeng-Lufeng-Shanwei center at the southern foot of Lianhua Mountain and the Qingyuan-Fogang-Longmen center in the Beijiang River valley. Among these, the Enping-Yangchun-Yangjiang center is the region which is first affected by the southwest monsoon, and there are many horn-mouth terrains along its coastal areas. In the region, the mountain chains of Yunwu Mountain are at right angles or oblique to the southwest airflows, making the regions before the windward slope a heavy rainfall area. Meanwhile, this region is susceptible to tropical weather systems. In the Haifeng-Lufeng-Shanwei center, the marine warm and wet airflow is affected by the intense uplift of the Lianhua Mountain oblique to its inflow direction, and its coastal areas are frequently affected by the tropical cyclones. Therefore there is plentiful precipitation, heating and dynamic energy in this region. As for the Qingyuan-Fogang-Longmen center, because the southwest warm-moist airflows passing through the Pearl River Delta plain are obstructed and lifted by Daluo Mountain, Bijia Mountain and Jiulian Mountain in the Qingxin region of Qingyuan, frontal precipitation are formed. There is less precipitation in the Meizhou City, Zhaoqing City and north of Shaoguan City. The minimum value is at Xuwen station, and the annual precipitation is 1,320 mm.

As shown in Fig.2b, there are many rainy days in Guangdong, and the average annual precipitation days are between 110d and 190d. Most of the northern mountainous areas of Guangdong and the central part of western Guangdong have a large number of precipitation days, with average annual precipitation days more than 160d. The maximum precipitation days occurred in the "Lianzhou-Liannan-Lianshan-Yangshan" region, and there were 187 precipitation days at Lianzhou Station. However, there were fewer precipitation days in the coastal areas, especially in the coastal regions of eastern Guangdong and Leizhou Peninsula, where there were 130d or fewer precipitation days throughout the year on average. There are great differences in spatial distribution characteristics of the annual average precipitation and the annual average precipitation days in Guangdong throughout the year, and there are non-corresponding relationships between the high value regions of precipitation and the high value regions of precipitation days. This indicates that there are significant differences in precipitation characteristics in different regions of Guangdong. However, the precipitation contribution rate and precipitation days of downpour in the Qingyuan-Fogang-Longmen center were below those of the other two rainstorm centers, but significantly higher than its surrounding regions where the precipitation contribution rate and precipitation days were respectively over 10% and 1.5d.

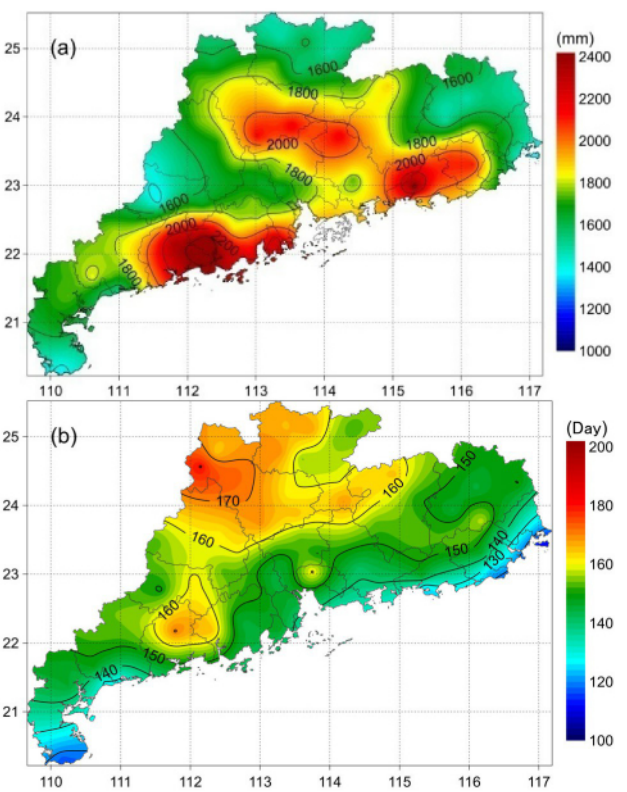

Figure 2. Annual average precipitation (a) and precipitation days (b) distribution in Guangdong from 1961 to 2010.

In order to further study the causes of the differences of different regional precipitation characteristics in Guangdong, the spatial distribution of contribution rates and precipitation days of different grades of precipitation are analyzed, and the results are shown in Figs.3 and 4, respectively. The statistical results show that the contribution rate of precipitation and precipitation days of light, moderate and heavy rain are decreasing from the northern part of Guangdong to the coastal areas. The high contribution rate (greater than 18%) and the large number of precipitation days

(more than 110d) of light rain are mainly concentrated in the northern and western regions of northern Guangdong. The large value areas of contribution rate and precipitation days of moderate rain are mainly concentrated in the northeast of northern Guangdong, in which the contribution rate is more than 30%, and the precipitation days exceed 30d. The high contribution rates (about 30%) of heavy rain are mainly concentrated in Zhaoqing and Meizhou but the large numbers of precipitation days (more than 15d) of heavy rain are mostly concentrated in the three rainstorm centers. The contribution rate and precipitation days of rainstorm and downpour increase from northern Guangdong to coastal areas. The contribution rate and precipitation days of rainstorm in the three rainstorm centers are much higher than in other areas, with contribution rate higher than 24% and precipitation days more than 7d. The contribution rate and precipitation days of downpour in the coastal areas of Guangdong are much higher than those in the inland areas. The contribution rates and precipitation days of downpour in Haifeng-Lufeng-Shanwei center are higher than 21% and 2.5d, respectively. The contribution rates of downpour in Enping-Yangchun-Yangjiang center are even higher than 24%, and the precipitation days of downpour are more than 3d.

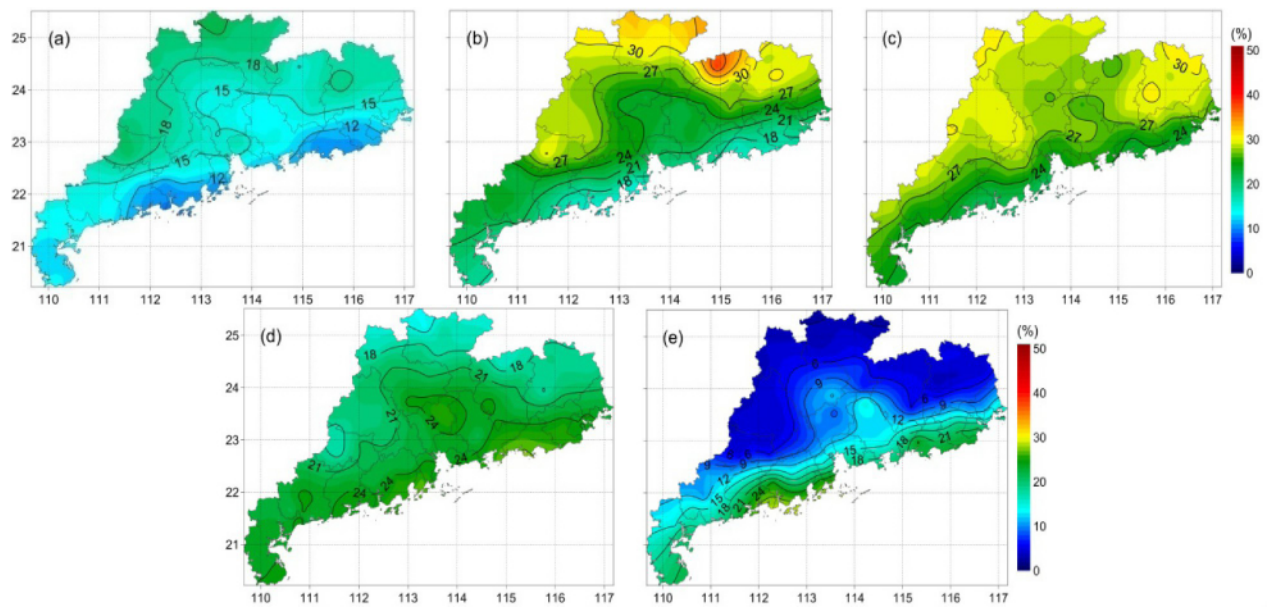

Figure 3. Spatial distribution of contribution rate of different precipitation grades in Guangdong from 1961 to 2010. Light rain: (a); moderate rain: (b); heavy rain (c); rainstorm: (d); downpour (e).

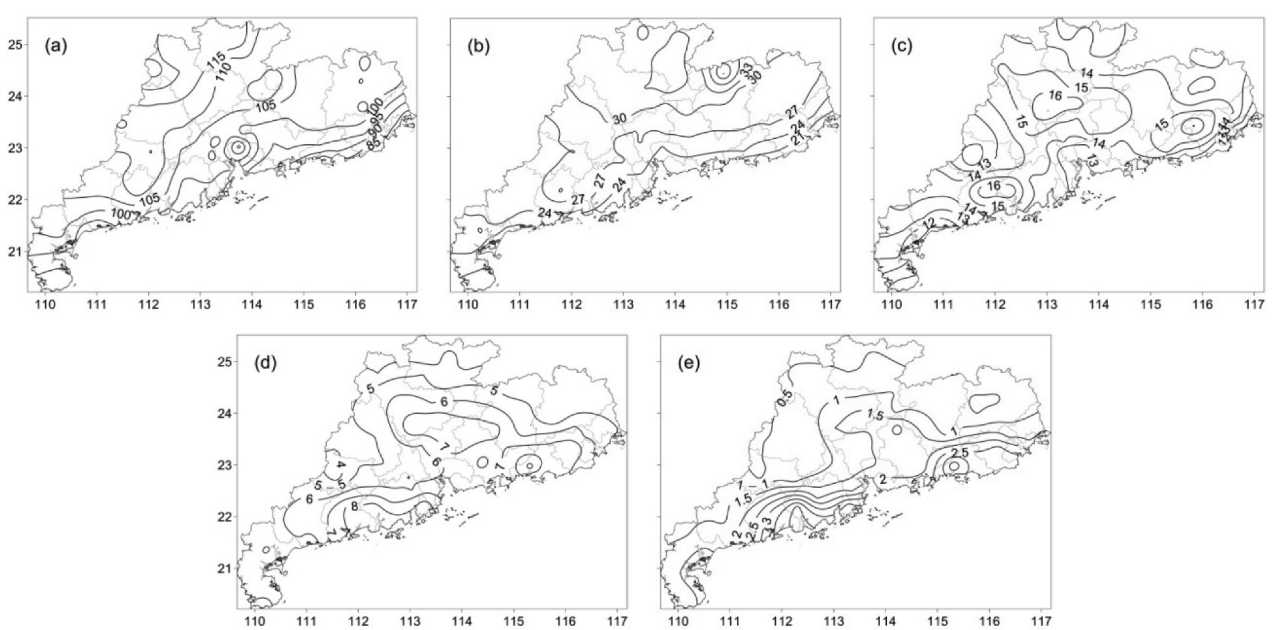

Figure 4. Spatial distribution of average precipitation days of different precipitation grades in Guangdong from 1961 to 2010. Light rain: (a); moderate rain: (b); heavy rain (c); rainstorm: (d); downpour (e).

It can be seen that the contribution rates and precipitation days of light rain and moderate rain in northern Guangdong are relatively higher than in other areas. However, the contribution rate and precipitation days of heavy rain and the above level are much less than in other areas, responsible for a lot of precipitation days in the northern part of Guangdong, but the annual average precipitation is not much. Higher contribution rates and more precipitation days of heavy rain and above heavy-rain level in the three rainstorm centers caused fewer the precipitation days but the annual average precipitation are significantly higher than that of other areas. The above reasons are the fundamental cause of the obvious difference between the distribution of annual average precipitation and precipitation days in Guangdong.

3.2 *Monthly variation characteristics of precipitation*

The average monthly precipitation and precipitation days of Guangdong from 1961 to 2010 are shown in Fig.5, in which the proportions of hierarchical precipitation of the monthly precipitation and precipitation days are also provided. The monthly precipitation and precipitation days of Guangdong show unimodal structures. The average monthly values, especially precipitation, were quite different. The maximum value of the monthly average precipitation and the precipitation days appeared in June, where the precipitation was as high as 313 mm and the precipitation days were 19d. The lowest precipitation occurred in December, only 31mm. November was the month with the least number of precipitation days, only 5.6d. Throughout the year, rainfall mainly concentrated in April to September, where the monthly average precipitation exceeded 150mm and the total precipitation was approximately 80% of the annual precipitation. Meanwhile, there were more than 15 precipitation days every month and the total precipitation days accounted for 65% of the annual precipitation days. Therefore, the period from April to September was called the rainy season (wet season) of Guangdong. Additionally, the rainy season of Guangdong was composed of two stages, namely the annually first rainy season (April –June) and the annually second rainy season (July–September). At the first stage, the precipitation was mainly caused by low troughs of frontal surfaces, so the dominating precipitation was the frontal precipitation and rainstorms occur over an extended scope. At the second stage, the precipitation was usually caused by the tropical cyclone. During the period from January to March and from October to December, the air in Guangdong was very dry, so there was little precipitation; the monthly precipitation was less than 100mm, and there were fewer than 10 precipitation days. These periods were called dry seasons (less rainy seasons). The more numerous precipitation days and the higher proportion of precipitation and precipitation days of heavy rain and above-heavy-rain level in the rainy season were the fundamental reasons that the precipitation in the rainy season of Guangdong was far higher than that of the less rainy season.

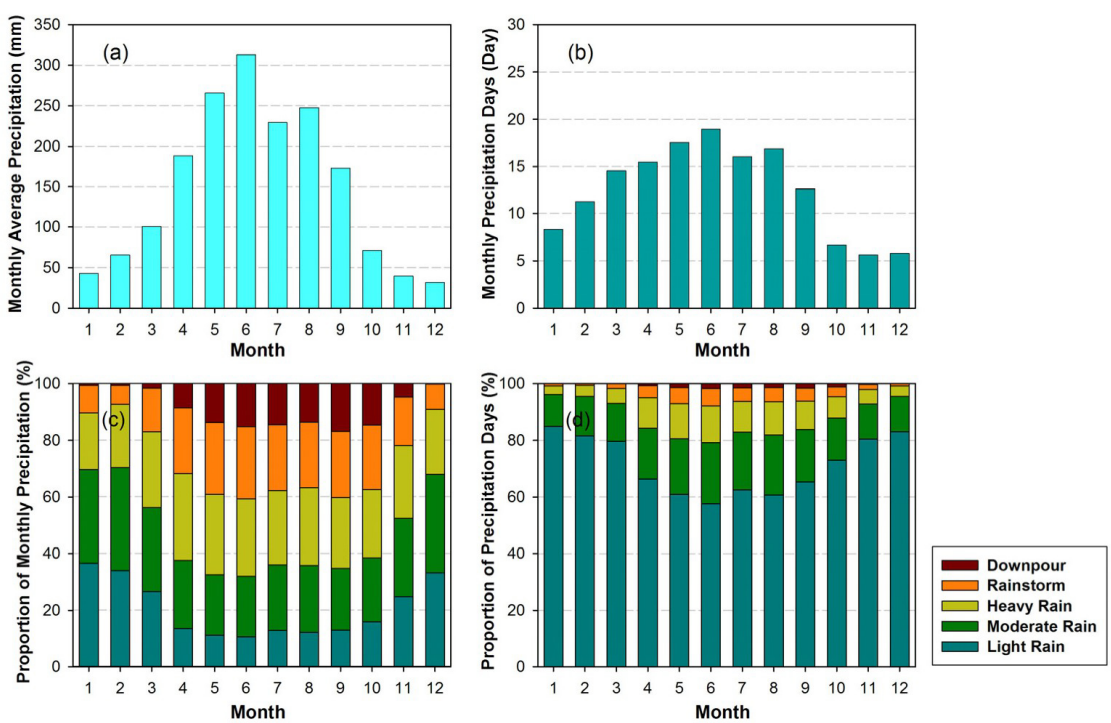

Figure 5. Distribution of monthly precipitation (a) and precipitation days (b), and percentage of monthly precipitation (c) and precipitation days (d) in Guangdong from 1961 to 2010.

In order to better compare the difference in the precipitation characteristics of the rainy season and less rainy season in different regions of Guangdong, statistics were provided for the distribution of precipitation, precipitation contribution rate and precipitation days in the annually first rainy season, annually second rainy season and less rainy season in this paper as shown in Fig.6. The annually first rainy season was the dominating precipitation period, in which the precipitation accounts for 40% of the total annual precipitation or more. Precipitations of the three rainstorm centers during the annually first rainy season were far higher than that of the surrounding regions, especially in the Qingyuan-Fogang-Longmen rainstorm center, where the precipitation was more than 1,000mm. In the annually second rainy season, the precipitation was mainly caused by the tropical cyclone, so the precipitation and precipitation days tended to reduce from the coastal areas to the northern areas, and the declining trend of precipitation was especially apparent. In the Enping-Yangchun-Yangjiang and Haifeng-Lufeng-Shanwei rainstorm centers, the precipitations during the annually second rainy season were significantly higher than that of the surrounding regions, wherein the precipitation in the Enping-Yangchun-Yangjiang rainstorm center even exceeded 900mm.

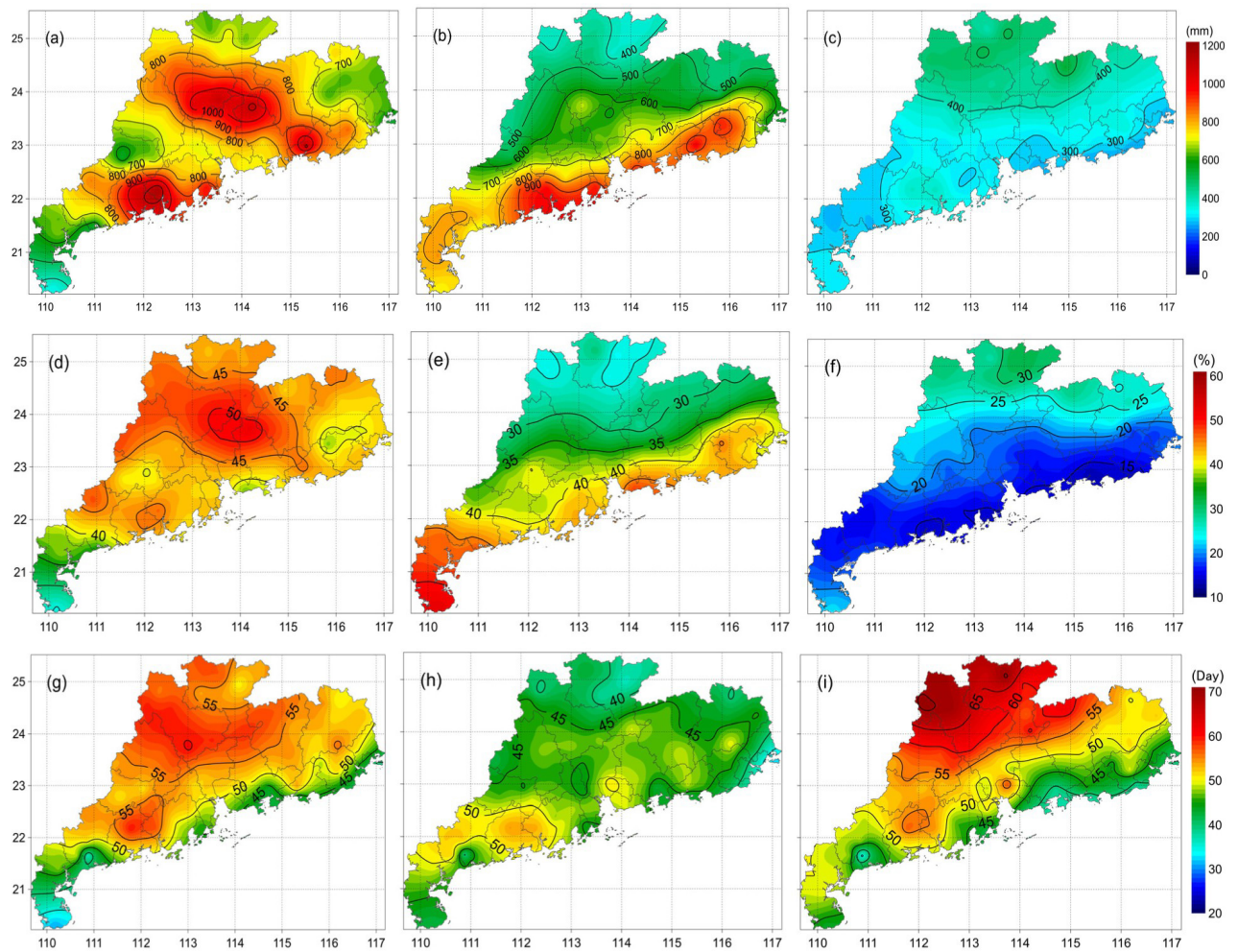

Figure 6. Precipitation distribution (Row 1), precipitation contribution rate distribution (Row 2) and precipitation day distribution (Row 3) during the annually first rainy season (left column), annually second rainy season (middle column) and less rainy season (right column) in Guangdong from 1961 to 2010.

According to the precipitation contribution rate, the precipitation contribution rate of the Qingyuan center during the annually first rainy season was the maximum (50% approximately), but it was only 30% in Leizhou Peninsula. Whereas the precipitation contribution rate tended to decrease from northern areas to coastal areas during the annually second rainy season; and the precipitation contribution rate of Leizhou Peninsula was 50% due to the tropical cyclone precipitation. During the less rainy season, the precipitation contribution rate apparently tended to increase from northern areas to coastal areas, where it was more than 25% in most of the northern areas of Guangdong and approximately 15% in the coastal areas of Guangdong.

There were more precipitation days in the northern and middle regions of Guangdong during the annually first rainy period, but fewer in the coastal areas; especially in the Leizhou Peninsula, where there were only 35 precipitation days. There were more precipitation days in the Yangjiang center, northern Maoming and northern Zhanjiang and fewer precipitation days in northern Guangdong during the annually second rainy season. In the less rainy season, precipitation was mainly caused by the southward-advancing cold air, the precipitation and precipitation days tended to decrease from the northern areas to the coastal areas, so the precipitation days decreased more significantly.

3.3 *Changing trend of time series of hierarchical precipitation*

The year-by-year trend of precipitation in different grades in Guangdong from 1961 to 2010 is given in Fig.7. The results show that the total precipitation days tended to decrease, the linear change rate was −2.19 d/(10a), but it is not significant (P>0.05). The precipitation days of light rain decreased significantly (P<0.05) with a linear change rate of −2.55 d/ (10a). The precipitation days of moderate rain fluctuated in a balanced state and did not change significantly. The precipitation days of heavy rain, rainstorm and downpour tended to increase, their linear change rates were respectively 0.20, 0.13, 0.04 d/ (10a) and their tendency was not significant (P>0.05). In summary, the precipitation days of light rain significantly decreased, the precipitation days of heavy rain or higher grades increased in Guangdong from 1961 to 2010, but the total precipitation days tended to decrease.

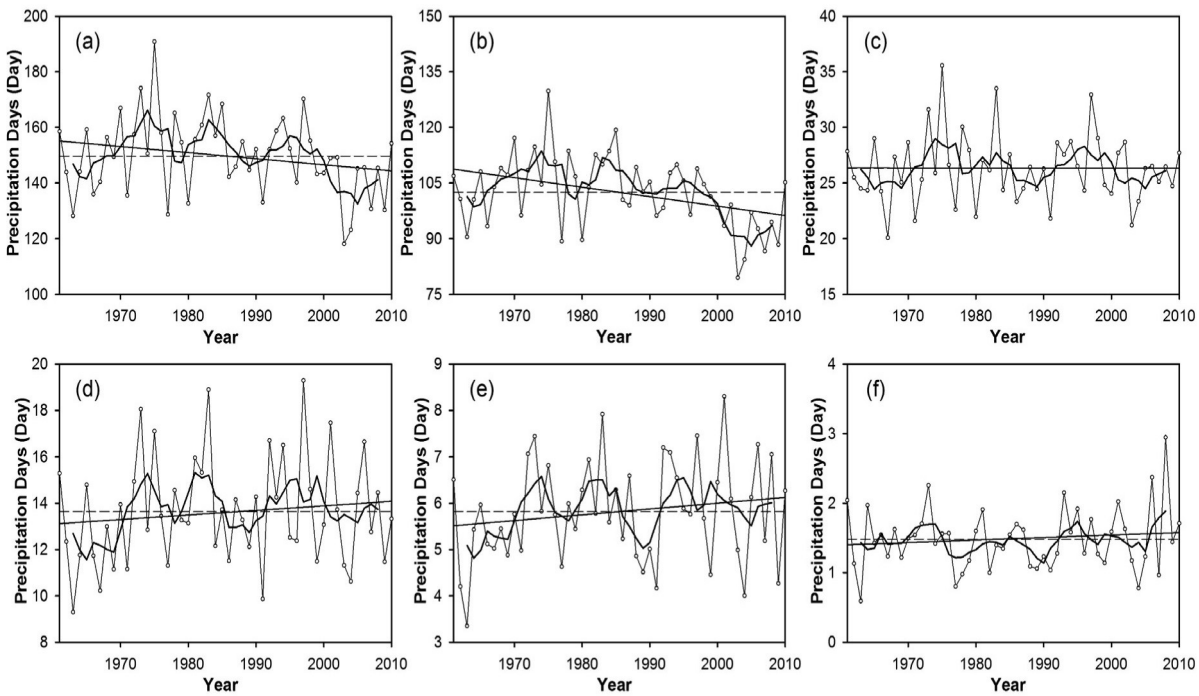

Figure 7. Precipitation days at all levels (solid line) and their linear change tendency (dotted line) in Guangdong from 1961 to 2010. Total precipitation: (a); light rain: (b); moderate rain: (c); heavy rain: (d); rainstorm: (e); downpour (f).

Figure 8 shows the year-by-year trend of precipitation contribution rate at all levels in Guangdong from 1961 to 2010. The annual average precipitation in Guangdong tended to increase, its linear change rate was 38.26 mm/ (10a) and its tendency was not significant (P>0.05). The contribution rate of light rain tended to significantly decrease (P<0.05), and its linear change rate was −0.38 %/(10a). The contribution rate of moderate rain decreased slightly, but its change tendency was not significant. The contribution rate of heavy rain, rainstorm and downpour tended to increase, with linear change rates of 0.17%, 0.31% and 0.14% (10a) $^{-1}$, respectively, but the tendency was not significant (P>0.05). The results show that the contribution rate of light rain and moderate rain tended to decrease, but the contribution rate of heavy rain or higher grades increased, making the annual precipitation increase accordingly.

Comprehensive analysis of Fig.7 and Fig.8 show that the number of precipitation days of Guangdong from 1961 to 2010 tended to decline, but the total precipitation tended to increase. The number of precipitation days of light rain and its precipitation contribution rate were showing significant downward trends. Meanwhile, the precipitation days of heavy and/or heavier rain and their precipitation contribution

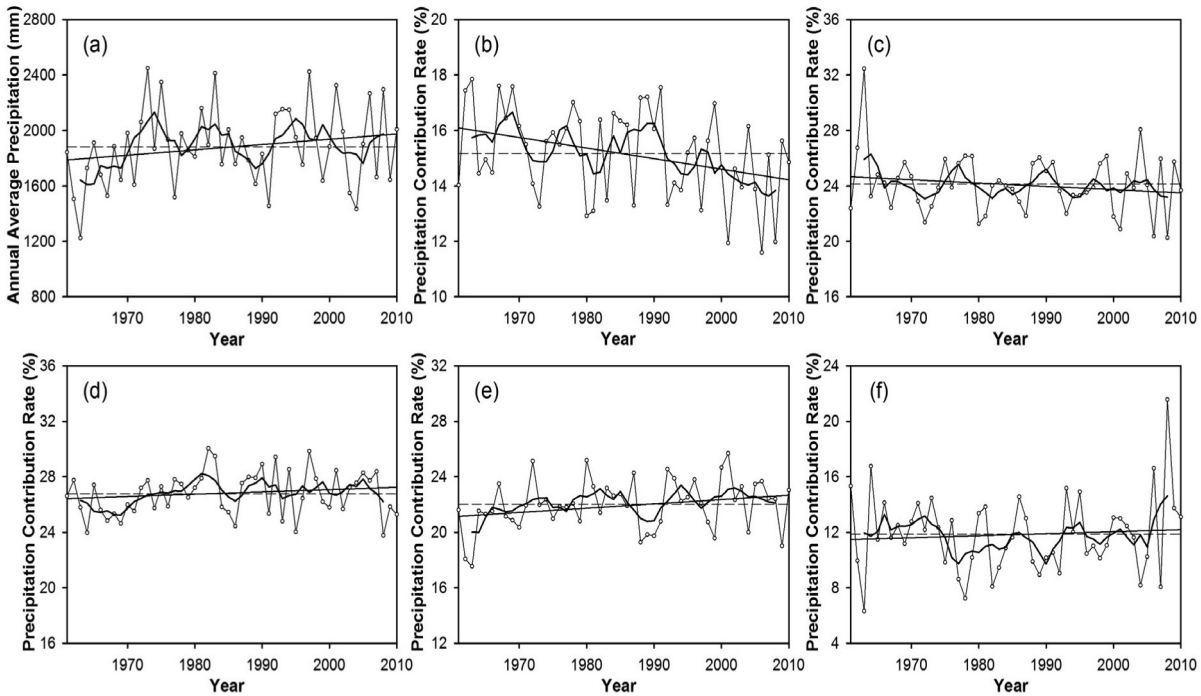

Figure 8. Precipitation contribution rate at all levels (solid line) and their tendencies (dotted line) in Guangdong from 1961 to 2010. Total precipitation: (a); light rain: (b); moderate rain: (c); heavy rain: (d); rainstorm: (e); downpour (f).

rate tended to increase, especially in the past 10 years, the frequent short-term heavy precipitation in different areas of Guangdong caused the precipitation contribution rate of heavy and/or heavier rain to increase year by year, which resulted in the apparent increasing tendency of annual precipitation.

4 DISCUSSION AND CONCLUSIONS

Based on the daily precipitation data obtained by observation stations from 1961 to 2010, the climatic characteristics and change tendency of hierarchical precipitation in Guangdong Province are analyzed in this study. The analysis supports the following conclusions.

(1) The annual average precipitation in Guangdong were mostly between 1,500 and 2,000 mm, so there were plentiful precipitation. There were great regional differences in the precipitation climate characteristics in Guangdong, and the precipitation and precipitation days in different regions were very different. The difference in the precipitation days in the different months was less than that of the precipitation. The precipitation days in the dry season were not significantly fewer than those of the wet season, but the precipitation intensity was weaker. There were not only more precipitation days in the rainy season than that in the less rainy season, but also the precipitation intensity was greater.

(2) In the past 50 years, the regional difference in the precipitation days of light rain and moderate rain in Guangdong was small. The high value centers of precipitation days of heavy rain, rainstorm and downpour were mainly concentrated in the three rainstorm centers of Guangdong. The amount of precipitation days tended to increase gradually from north to south, and it decreased rapidly as the precipitation grade increased. The precipitation contribution rate of light rain, moderate rain and heavy rain tended to decrease from the northern areas of Guangdong to the coastal areas, but the precipitation contribution rate of rainstorm and downpour tended to increase from the northern areas of Guangdong to the coastal areas.

(3) The precipitation days of light rain has significantly decreased, and the precipitation days of heavy rain or higher grades increased in Guangdong from 1961 to 2010, but the total precipitation days still showed downward trends. The contribution rate of light rain and moderate rain in Guangdong tended to decline, while the contribution rate of heavy and/or heavier rain tended to increase, making the annual average precipitation increase accordingly.

The precipitation days and the precipitation contribution rates of precipitation at different grades have greatly changed in Guangdong from 1961 to 2010. The total precipitation days and total light rain days tended to decrease, which were consistent with the research results of preceding study [33]. However, the precipitation days and the precipitation contribution rates of rainstorm and downpour tended to increase, and they were mainly concentrated in the three rainstorm centers of Guangdong, which have significant influences on floods and other disasters. Therefore, meteorological

departments and local departments for wind, flood and drought prevention are recommended to enhance the issuance of weather warnings and prevention measures for the three rainstorm centers to safeguard the lives and property of the population and reduce the losses to the economy.

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